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Incredible Tale of Texasgulf Cane Creek No. 7 Well and Anisotropic Extension Fracture Permeability, Paradox Basin, Utah

by

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ABSTRACT

Normal faults and associated extended joints form an extremely permeable zone in Pennsylvanian and Permian limestones and arkoses along the crest of the Cane Creek salt growth anticline of southeastern Utah. These same rocks in unfaulted states comprise an extensive regional confining layer sequence.

Fluids in the fault zone are sodium chloride - hydrogen sulfide brines which have bleached all permeable flow paths within the units. Bleaching patterns in outcrops reveal that circulation in the fault zone is largely restricted to the fault planes and nearby extended joints. Orthogonal joints within the fault zone are also bleached but to a lesser extent. In contrast, bleaching of all joints a short distance from the faults is rare. The highly anisotropic permeability distribution observed is characterized by maximum principal permeability tensors oriented parallel to the strike of the faults and minimum principal tensors perpendicular to the fault planes.

The productive zone has a transmissivity considerably in excess of 10^5 gallons/day-foot parallel to the strike of the faults. Fracture permeability is attributed to minute separations developed along faults and

joints as the rocks containing them underwent extension perpendicular to the strike of the anticline. The causitive extensional stress regime was imposed on the rocks as they were bent and stretched over the growing core of the anticline.

The general conclusion of this article is that extensional tectonic regimes are ideally suited for imprinting fracture permeability on brittle rock sequences. Such fractures include extensional joints and high angle normal faults. Small offsets appear to favor development of porosity because surface irregularities in the fracture planes are not ground off thereby forcing the facing surfaces to separate and gouge development is minimized.

PURPOSE

Rarely has it been possible to document fracture induced anisotropic permeabilities as clearly as is feasible along the Cane Creek anticline of Utah. This article will describe the extensional fracture system within brittle Paleozoic rocks along the crest of the anticline that hosts a productive brine filled aquifer. Three dimensional definition of the fracture system is possible using a unique combination of available surface, mine and drillhole data. The productivity of the fault zone will be illustrated - abate qualitatively - by the unprecedented drilling history for the Texasgulf Cane Creek number 7 injection well.

The fascinating story of well 7 will be prefaced by succinct descriptions of the Texasgulf solution mining operation and the tectonic regime responsible for the emplacement of the anticline and the extensional fractures contained within it. These considerations will set the stage for the drilling of well 7 and the hydrologic insights that came from the hole.

ACKNOWLEGMENT

Data which forms the basis for this article was generously released to the writer by the Texasgulf Chemicals Company through mine superintendent R. S. Higgins. Details pertaining to the drilling of well 7 are from Willard Pease Drilling Company (1971) in records held by Texasgulf Chemicals Company. The enthusiasm of mine personnel, particularly Bob MacAdams, Environmental Supervisor, toward publishing this study is especially acknowledged. Don L. Baars, petroleum geology consultant, Evergreen, Colorado, provided stratigraphic correlations for the gamma ray-neutron geophysical logs used to prepare this article.

POTASH MINE

The Texasgulf potash mine and processing facilities are situated in an amphitheater on the west side of the 2,000 foot deep canyon of the Colorado river 7 miles southwest of Moab, Utah. See Figure 1. The sylvite ore zone occurs in Salt 5 (Hite, 1968) of the Pennsylvanian Paradox Formation (Figure 2) which lies 3,000 feet below the land surface at the site. Construction of the 2,789 foot deep main access shaft to the ore zone was begun in 1961 on the northeast limb of the Cane Creek anticline. Lateral drifts were dug from the shaft toward the axis of the anticline which intersected the ore layer. Ore extraction began in 1965 using conventional room and pillar mining techniques.

Conventional mining proved to be increasingly difficult. The mine was found to be gassey from the onset of operations, a not unexpected situation because the Paradox Formation and overlying Honaker Trail Formation are known hydrogen sulfide and hydrocarbon producers in the region. For example, crude oil was encountered in the Honaker Trail Formation at a depth of 1,510 feet during the sinking of the shaft. Worse, combustible gasses, primarily methane, were encountered during mining operations in the Paradox Formation, a problem that continually plagued operations. Eighteen miners were killed on August 27, 1963, in a gas explosion during construction of the lateral drifts between the main shaft and ore horizon (Westfield and other, 1963). In addition, folds within the ore horizon resulted in overly steep tunneling conditions within the mine (Phillips, 1975).

Conventional mining ceased in 1970. By this time an underground area of more than 500 acres had been intensively mined under a four $mile^2$ region centered under the crest of the anticline. Approximately 150 miles of passageways had been dug containing a void volume of 800×10^6 gallons (Phillips, 1975).

The mine was converted to a solution mine in 1971. The plan was to deliberately flood the mine with Colorado river water through a series of injection wells. The water would be used to dissolve the potash and associated sodium chloride, and the resulting brine would be returned to the surface through recovery wells. Potash extraction from the brine would be through an evaporation and chemical refining process.

All aspects of this design were implemented. However, as will be revealed, the initial flooding of the mine was not accomplished by the use of Colorado river water. River water is currently used in the process, preferred over ground water in the region because of its low sodium chloride content. The average residence time for brine in the mine is about a year.

SALT CORED CANE CREEK ANTICLINE

The focus of this article is a brine filled, highly permeable normal fault system along the crest of the Cane Creek anticline. The fractures occur in a 2,500 to 3,000 foot section of strata that otherwise serves as extensive regional confining layer. The geometry of the fractures are best understood by examining the mechanism responsible for creating them in the anticline. Consequently this section will (1) describe the development of the Cane Creek anticline, and (2) examine the stress regime within the evolving fold that produced extensional faulting along its crest.

The Texasgulf potash operation lies within the 15,000 square mile Paradox geologic basin of southeastern Utah and southwestern Colorado. The basin is defined as that area underlain by the Pennsylvanian Paradox evaporites which consist primarily of sodium chloride, with subsidiary beds of potassium chloride (potash), gypsum, and interbedded limestones, shales and clastics (Wengerd and Matheny, 1958; Baars and others, 1967). Maximum original salt thicknesses in the Paradox Formation reached about 4,000 to 5,000 feet. The salts were in turn successively buried by 8,000 to 12,000 feet of younger sediments at the Texasgulf locality, more than half of which are now eroded from the area.

The Paradox salts are best viewed as a viscous liquid rather than as a solid. When loaded, they flow. The burial of the salt by younger sediments provided for continuous lithostatic loading of the salt which ultimately resulted in the development of salt flowage structures throughout the Paradox Basin. Flowage of the salt began as soon as the salt was deposited and has continued at waxing and waning rates to the present (Cater, 1970).

The most dramatic class of salt flowage structures in the Paradox Basin is a series of northwest trending salt cored anticlines. The Cane Creek anticline, site of the Texasgulf mine, is a large yet regionally minor salt growth anticline in this system.

Salt accretion in the core of the Cane Creek anticline was sourced by influx of Paradox salts from adjacent areas. The salt growth process has taken place continuously but at variable rates since at least Permian time, thus allowing the anticline to grow through time. Regional subsidence rates remained slightly greater then rates of uplift along the axis of the anticline until late Cretaceous time. The result as shown clearly on Figure 3 was the successive thinning of all strata deposited over the axis.

Uplift and erosion of the region commenced in late Cretaceous time allowing for erosional stripping of thousands of feet of Cretaceous and older rocks. This tectonic phase is continuing. The cumulative Cretaceous to recent uplift at the Texasgulf mine has been approximately 2 miles. Direct consequences of the uplift are that the Paradox salts in the Cane Creek anticline now lie above sea level, and the Colorado river has eroded deep canyons throughout the region.

FAULTS IN CANE CREEK ANTICLINE

All the faults that occur along the Cane Creek anticline - illustrated on Figure 4 - are high-angle normal faults that owe their origin to extension within brittle beds folded across the rising axis. Notice from Figure 5 that the strikes of the faults cluster about the axis of the fold so that they strike perpendicular to the direction of maximum extension within the deforming beds. The steep dips of the faults and downward convergence of oppositely dipping sets reveal a vertical orientation for the maximum principal compressive stress tensor during fault emplacement. The minimum principal stress was oriented ~~and~~ so that they strike perpendicular to the direction of maximum extension within the deforming beds. The steep dips of the faults, averaging 80 degrees, and downward convergence of oppositely dipping sets, reveal a vertical orientation for the maximum principal compressive stress tensor during fault emplacement. The minimum principal stress was oriented horizontally and perpendicular to the fold axis. Vertical displacements along the faults are volume compensations for space created as the brittle layers lengthened through bending. In essence the faulting allowed the deforming beds to thin as they stretched.

Far more important from the hydrologic perspective is that the extensional stress regime in the Cane Creek anticline favored development of large but highly anisotropic permeabilities. Permeability enhancement occurred as a direct consequence of the lateral stretching of the deforming brittle units as they bent over the rising axis of the anticline. Fractures oriented perpendicular to the direction of stretching tended to open thus dramatically increasing permeabilities associated with them. Affected fractures in the Cane Creek anticline were those having orientations parallel to the axis including preexisting and developing joints, and concurrently developing volume compensating normal faults.

It should be emphasized that the rocks within the anticline underwent extension, however it is unlikely that the stress regime at depth within the anticline ever reached a tensional state - one in which the minimum principal stresses perpendicular to the axis became outwardly directed. Rather the stresses within the deforming rocks remained inwardly directed resulting in net compression across all fracture planes. Such conditions would seem to preclude the development of permeability regardless of whether the bed was extending or not. However field examination of extended fractures reveals that brittle rocks are readily capable of transmitting inwardly directed stress at specific load points across the planes of fractures. The load points are localized at geometric irregularities on the fracture surfaces. Consequently minute offsets along extending joints and small displacements along normal faults allow for the development of space within the fracture plane even while stresses are directed inward toward those planes. It appears that small displacements on individual fractures generally provide a better opportunity for development of fracture permeability than large displacements. This follows because with small offsets there is less opportunity for surface irregularities to be ground off and less opportunity for development of gouge between the moving surfaces.

All measured displacements along the Cane Creek faults are small - none were found with more than 100 feet of stratigraphic offset. The faults do not extend above the top of the brittle Elephant Canyon Formation in the vicinity of the mine, however, larger displacement faults in the same system east of the river extend upward and attenuate in the lowermost Triassic units. It is clear from the observed relationships that the faults attenuate within the ductile overlying units which deform through a combination of volume compensating folding and thinning through processes of minor ductile flowage and brittle jointing. Also contributing to upward attenuation is the fact that the successively younger units have been subjected to both a shorter history of deformation and smaller degree of bending.

Much of the fault zone exposed on the land surface at the level of the Elephant Canyon Formation is underlain by the Texasgulf mine. Detailed mapping within the mine (Texas Gulf Sulphur Company, 1970) reveals that the faults do not project downward to the mined horizon demonstrating conclusively that they die out downward in the lower Elephant Canyon Formation and Honaker Trail Formation. See Figure 4.

JOINTS IN CANE CREEK ANTICLINE

Joint orientations shown on Figure 5 were taken from aerial photography and represent the strikes of the locally prominent extensional joint set. Joints from Permian through Jurassic stratigraphic levels were sampled within the fold, a fact facilitated by the large topographic relief and excellent quality of exposure in the map area.

Field assessments of the jointed outcrops reveal the following: (1) Most joints in the area are vertical or subvertical. (2) Most of the prominently jointed outcrops consist of thick brittle sandstones or limestones. (3) All outcrops are characterized by the development of a very weakly defined set of tightly closed orthogonal or sub-orthogonal joints that have spacings which are commonly three or more times as distant as spacings between the prominent extensional joints plotted. (4) Figure 5 reveals that the extensional joints mapped are sub-parallel to the axes of maximum curvature on the folded beds in which they occur. Where faults and joints occur together they have coincident strikes providing confidence that the joints plotted in fact owe their origin to extension.

Joints have the potential for imprinting significant fracture permeability on otherwise poorly transmissive rocks. There is no question that the extensional joint sets in the Cane Creek anticline increased host rock permeabilities, however, even with imprinted joints the permeabilities associated with the rocks remained small. Evidence for this lies in the fact that seeps localized along joints in the Cutler and Elephant Canyon formations in the vicinity have negligible discharges which are little different from seep rates observed from unjointed parts of the same units.

FAULT VERSUS JOINT PERMEABILITY

Fortunately a qualitative comparison can be made between the relative importance of fault and joint induced permeabilities. Ground waters found in the Elephant Canyon and older rocks are hydrogen sulfide charged brines. Circulation of these reducing waters toward the Colorado river results in alteration of the host rocks through the reduction of iron oxides. Consequently zones of past circulation are readily distinguished as bleached zones in outcrops. Bleaching was found to be rare even along extensional joint sets at locations distant from the normal faults along the crest of the Cane Creek anticline. However, as shown on Figure 6, bleaching of both extended joints and faults in the fault zone is dramatic revealing the overwhelming importance of extensional faulting in imparting permeability to the rocks.

MAIN SHAFT

The 2,789 foot main shaft for the mine is located on the northeast limb of the Cane Creek anticline, 1.15 miles from the axis. It served as a large diameter well during construction which yielded a considerable amount of information on the hydrologic character of the unfaulted section of the

Elephant Canyon and Honaker Trail formations which was penetrated. The hole was completed with a concrete liner having an inside diameter of 22 feet.

The rocks below 90 feet were found to be saturated and the water was under artesian conditions. Sodium chloride brines were encountered below 390 feet. Texasgulf employees conducted a detailed inventory of the locations of inflows and sampled the waters in the shaft on September 18, 1963. The brine analyses are reproduced here as Table 1 and reveal that total dissolved solids contents increase with depth.

Total measured inflows to the shaft were less than 50 gallons/minute, hardly a significant yield from a 2,789 deep, 22 foot diameter well. The rates of inflow demonstrate conclusively that the unfaulted Elephant Canyon and Honaker Trail formations are regional confining layers. This conclusion is supported by drillstem test derived hydraulic conductivities of 1.6×10^{-5} to 5.1×10^{-1} gallons/day-foot^2 presented in Thackston and others (1984, Table 4-2) for these same rocks. Huntoon (1979) and Richter (1980) observed that contributions to the permeability in unfaulted Permian and Pennsylvanian sections included in decreasing order of importance (1) joints and partings along bedding planes, (2) intergranular porosity, and (3) intercrystalline porosity. Even in combination, these factors do not comprise sufficient bulk permeability to lift the rocks out of the confining layer class.

With the experience of the 22 foot diameter shaft behind them, it comes as no great surprise that the Texasgulf planners gave little further attention to ground water.

WELL 7

Injection well 7 was spudded on the crest of the Cane Creek anticline on December 27, 1970, by Willard Pease Drilling Company Rig number 3. The target depth was the roof of the underlying mine 3,016 feet down. The mine was largely empty because only a small amount of water had been pumped into it up to this time. Drilling was begun with air.

On December 29th Floyd Whinery "mashed end off index finger of right hand" while guiding a drill bit down to the turn table (Willard Pease Drilling Company, 1971). This was a bad omen. Whinery was back on the job at the beginning of the 8 am shift on January 1, but by this time the drillers had been forced to convert to mud because they had encountered uncontrollable quantities of brine under artesian conditions at a depth of 600 feet. They had unwittingly drilled into the extensional fractures in the Cane Creek fault zone.

Immediate and massive attempts were undertaken to seal off the unwanted production. On December 31 alone 303 sacks of Zeogel, 98 sacks of cotton hulls, and 104 sacks of Fibertex were pumped into the hole. The decision was made to continue drilling without returns, knowing full well that the risks of twisting off the drill stem were high. Continued attempts to reestablish circulation would be taken but returns were always negligible. The final statistics are remarkable. Between a depth of 600 and 2,675 feet when attempts to introduce sealants were finally abandoned, the following quantities of additives in sacks were sent down the hole never to be seen again: Zeogel - 2,922; cotton hulls - 1,183; Fibertex - 1,175; lime - 14; Dicell- 143; Plugit - 226; Hyseal - 947; and Aqua Gel - 934. As expected twistoffs occurred, specifically at 2,130, 2,209, and

2,753 feet. Each time the drillers were successful in fishing the broken tools from the hole.

Despite the technical difficulties with lost circulation, the drillers reached the top of the salt at 2,338 feet letting them know they were now in the potentially dangerous Paradox Formation noted locally for overpressured gas. On January 13, at a depth of 2,838 feet and with approximately 2,400 feet of mud and brine standing in the hole, they drilled into an overpressured H_2S gas zone and the hole blow out. The blowout lasted four hours. A large quantity of water shot from the hole along with a shower of fist size rocks which broke many of the lights on the rig and which also shredded the string weight log then on the rig recorder. The significance of this event are two fold (1) the presence of such zones of overpressured gasses in the upper Paradox Formation sustain evidence that the faults along the crest of the anticline die out above the Paradox Formation and therefore cannot provide vertical conduits which would prevent the buildup of such pressures, and (2) formation premeabilities are very small allowing the gas zones to depressure without significant influx of distant gas.

There is no indication from available records that either the drillers or well site geologist worried about the ramifications of drilling close to the roof of the mine in a hole that would be loaded with a 2,600 foot column of mud and brine. The top of clastic 4 immediately above the mine was encountered at 3,010 feet as drilling continued into the late afternoon of January 13. With six feet to go, tool string weight hovered at 100,000 pounds.

Suddenly at 5:23 pm after drilling a couple more feet, the roof of the mine collapsed from the weight of the standing column of brine in the overlying hole and water began flooding down the uncased well into the mine. The weight of the drill column immediately shot to 200,000 pounds providing a direct measure of the drag imposed on it by water rushing down the well bore. Then the unprecedented happened. The flow past the drill bit caused the derick to rock back and forth, and the drill column sometimes rotated on its own. The driller sensing disaster immediately began the two hour process of pulling the drill column from the hole.

It was quickly ascertained that having a sodium chloride brine rushing into the mine was a less than desirable situation. Texasgulf employees feared that sodium chloride would plate the walls of the mine making recovery of potassium chloride difficult. The decision was made to set a bridge plug at 2,335 feet to stop the downward flow of water in the well. The plug was lowered to the desired depth on January 14. As soon as an attempt was made to inflate the plug, it and the lower 10 lengths of drill pipe unscrewed and were lost down the hole.

Fishing for the lost tools commenced on January 15th, a process that proved futile. Instead the fishing tools were in turn severely damaged. When removed from the hole eight cork screwed lengths of drill pipe comprised the bottom of the recovered string (Figure 7). The fishing tool and the bottom 16 lengths of pipe were found to have been sheared off and lost in the hole. A Schlumberger collar locator was called in to sound for the lost tools, however when the probe was lowered to a depth of 2,284 feet, it too unscrewed in the rushing water and was lost to the hole. Site geologist Henson (1971) wrote in frustration: "Fished five days and only succeeded in leaving more tools and drill pipe in hole."

In a final desperate effort to seal the hole, an 11-3/4 inch casing was run to 2,309 feet with 9 cement baskets on the outside. Once in place

200 sacks of cement were used to seal the outside annulus on January 19th. The cement washed away so the casing was hung off and the Pease rig was released January 20th.

The mine was unexpectedly filling with ground water from the overlying fracture zone along the crest of the anticline. The flow rate was unknown and out of control. Approximately 800 x 10^6 gallons would be required to fill the mine. If all had gone as planned this volume of water would have been injected from the Colorado River into the mine through several wells over a four month period in the spring of 1971 (Phillips, 1975). Instead, the brine filled fractures above the mine did the identical job through a single one foot diameter hole in two weeks, despite the fact that for the last 10 days the water could move only in the annulus outside of the 11-3/4 inch casing. On January 28th, the heads in the aquifer and mine had equalibrated. The average flow rate down the hole had been 90 feet^3/second.

Now that the flow had ceased, it became a relatively routine matter to set a bridge plug. A second drill rig was moved in on January 29th to pull the 11-3/4 inch casing and ream the hole to 14-3/4 inches. The new contractor, Mesa Drillers, ran the large bit to a depth of 3,209 feet, some 200 feet below the supposed bottom of the original hole. That proved to be a mistake because when the driller pulled the string out of the hole he discovered that the lower 21 sections of drill pipe were badly bent "indicating large salt cavities that allowed the drill pipe to lay over and wad up" (Henson, 1971).

A second Schlumberger collar locator was run down the hole and located the top of one lost string of pipe at 2,302 feet despite the fact that the hole had been reamed subsequent to the loss of that string. Being unable to recover the string, a bridge plug was set at 2,210 feet and backfilled in 3 stages with 1,727 sacks of cement to 1,710 feet (Henson, 1974).

The depth to water in well 7 on January 28, 1971, was 690 feet. On June 27, 1985, it was 460 feet. The transmissivity of the production zone can be estimated using the specific capacity equation if it is assumed that the 230 foot difference between the 1971 and 1985 measurements is representative of the drawdown that occurred in the aquifer during the filling of the mine in January, 1971. That transmissivity is 4×10^5 gallons/day-foot, a value which assumes an isotropic aquifer.

No information exists on the thickness of the production zone but using a highly inflated thickness such as 1,000 feet yields minimum hydraulic conductivities in the fault zone that are 3 to 7 orders of magnitude greater than those reported by Thackston and others (1984, Table 4-2) for unfaulted sections of the same rocks. The production zone in well 7 is highly anisotropic and is considerably less than 1,000 feet in thickness. Consequently the 4×10^5 gallon/day-foot transmissivity computed substantially under estimates the maximum principal transmissivity tensor which is oriented parallel to the strike of the faults in the production zone.

IMPORTANCE OF EXTENSION

The development of fracture permeability in the brittle Permian and Pennsylvanian rocks in the Cane Creek anticline nicely illustrates the tectonic imprinting of permeability on rocks that otherwise would be classified as confining layers. However, it is not simply the fact of fracturing that is important. Paramount is the fact that the fractures were caused by extensional tectonism. Extension operates to lengthen beds which internally deform by volume compensating thinning. The result in typical settings involving brittle rocks is fracture failure in the form of normal faults and imprinting of additional joints. Extensional fractures in simple cases are oriented perpendicular to the direction of maximum extension. The result is the development of highly anisotropic permeabilities with maximum values oriented parallel to the strikes of the fault systems, and minimum values oriented parallel to the direction of extension.

Net compressional stresses operate across all but the most near surface factures in such systems. Despite this fact, porosity can develop in the fracture planes, especially if the facing blocks displace sufficiently to cause load carrying surface irregularities to force the walls apart. Clearly then small displacements tend to produce greater permeabilities because surface irregularities are not ground off and gouge development is minimized.

The obvious requirement for good permeability development is the presence of brittle strata which will fail through fracturing under the imposed extensional regime. More ductile rocks such as the Mesozoic shales in the Cane Creek anticline deform through volume compensating flowage which tends to minimize the opening of fractures even if they are concurrently forming. Consequently the imprinting of fracture permeability on ductile rocks requires substantially greater net extension than is required for brittle rocks in the same environment.

Compressional tectonic regimes - those associated with thrust faults and many classes of folds - do not favor the development of fracture permeability. The explanation rests on the fact that compressional tectonics involves shortening and thickening of units, accompanied in flat lying strata by maximum compressive stresses across vertical fractures oriented perpendicular to the direction of shortening. Brittle failure can and commonly does take place in the form of thrust faults but the strong compression tends to produce less porosity in the planes of fracture than that gained through extensional failures.

The Cane Creek example presented here is a particularly simple structure in which the layers over the growing salt core were all subjected to extension. Most tectonic structures of similar scale were produced by more complex internal stress regimes, part of which can be extensional and which will favor the local development of permeability. For example, typical anticlines in the Wyoming foreland province were emplaced through regional crustal shortening - compressional - events. The anticlines are cored by basement thrust or reverse faults and the synclines are internally deformed by imbricate and conjugate sets of minor thrust faults. However, the crests of the anticlines situated above the leading edges of the coring thrusts are subjected to progressively increasing degrees of extension with elevation. Normal faulting of the anticlinal crests is common, particularly in brittle strata high in the fold. These extensionally deformed parts of the fold are commonly very permeable and the zones of permeability parallel the crest of the fold. In contrast, the fractures in all other parts of the structure are tightly closed.

Each type of structure should be examined to determine if parts of them deformed under extension. If so, the extended volume provides the best drilling target. In the example of the foreland anticlines, good targets exist even in structures owing their gross tectonic character to massive regional compression.

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Table 1. Water quality data for ground water sampled in the Texasgulf main shaft, Cane Creek anticline, Utah. Water quality analyses reported in percentages. Data from Texas Gulf Company (1970).

Depth[1]	Quadrant	Cl	SO_4	NaCl	Ca	Mg	Fe	Na	H_2O	Total Solids	pH	Specific Gravity
90	NW	.107	.009	.176	.02	.005	nil		99.83	.17	8.3	1.001
410	N	6.33	.34	10.43	.32	.08	nil	4.10	88.53	11.47	7.8	1.084
490	NW	6.66	.38	10.98	.29	.07	nil	4.22	88.02	11.98	7.8	1.087
490	SW	6.88	.37	11.34	.35	.03	nil	4.31	87.65	12.35	7.8	1.090
690	SW	8.16	.23	13.45	.48	.14	trace	4.88	85.37	14.63	7.6	1.105
963[2]	--	7.72	.38	12.73	.38	.03	.0002	4.28	86.19	13.48	7.6	1.101
1510[3]	NW	12.57	.40	20.72	2.61	.49	.0004	7.63	75.81	24.19	7.6	1.168

1. Depth in feet.

2. H_2S odor.

3. Oil present.

LIST OF ILLUSTRATIONS

1. Extensional faults along the Cane Creek anticline in the vicinity of the Texasgulf potash mine, Utah. The faults attenuate in both the upward and downward directions, hence they do not displace the rocks forming the rim of the canyon. U - up thrown side. D - down thrown side.

2. Lithology and hydrologic character of the rocks along the axis of the Cane Creek anticline, Utah.

3. View looking east across the axis of the Cane Creek anticline, Utah. Texasgulf potash evaporation ponds below center. Notice all strata thin over the axis of the anticline. Ꞧ k - Kayenta Formation, Ꞧ w - Wingate Sandstone, Ꞧ c - Chinle Formation, Ꞧ m - Moenkopi Formation, Pc - Cutler Formation. Ponds rest on the Elephant Canyon Formation.

4. Cross section through the Texasgulf Chemicals Company potash mine, Cane Creek anticline, Utah. Stratigraphic control from outcrops and Schlumberger Well Surveying Corporation (1957-1960). Wells used for stratigraphic control projected to line of section. Location of cross section on Figure 1.

5. Relationship between the strikes of 46 sets of extensional joints, 24 extensional faults, and fold axis in the brittle rocks overlying the Paradox salts in the vicinity of the Texasgulf potash mine, Cane Creek anticline, Utah.

6. Bleached zones adjacent to extended joints in the fault zone along the Cane Creek anticline, Utah, which reveal historic ground water flow paths through the fractures. Bleaching is rare along fractures located more than a few tens of feet away from the fault zone.

7. Cork screwed drill pipe recovered from the Texas Gulf number 7 injection well which was damaged during fishing operations on January 15, 1971. Notice the column sheared off below the joint in the foreground when the fishing tool and 16 lengths of pipe were lost to the hole.

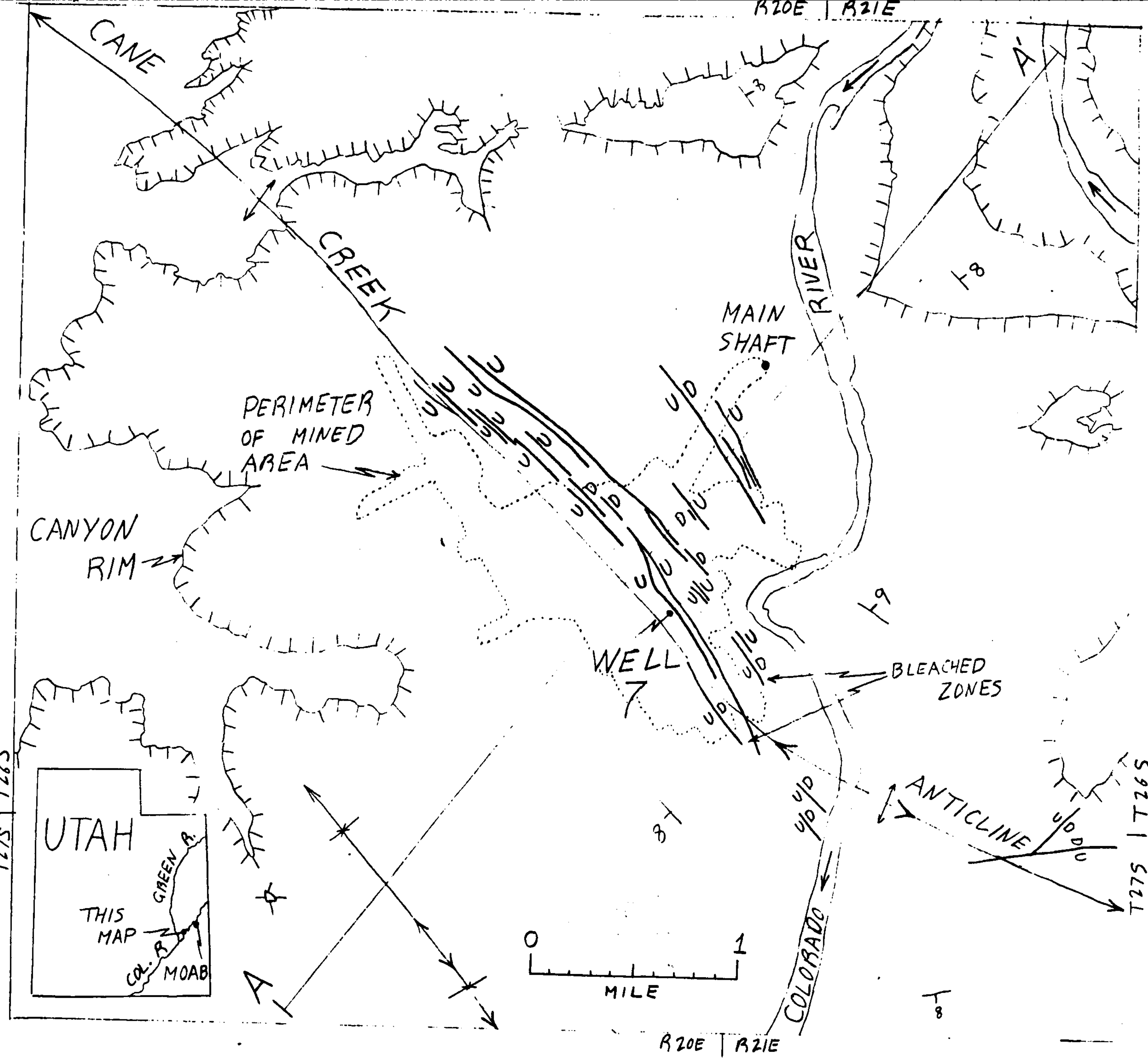
R20E | R21E
CANE
CREEK
RIVER
MAIN
SHAFT
PERIMETER
OF MINED
AREA
CANYON
RIM
WELL
7
BLEACHED
ZONES
ANTICLINE
COLORADO
T26S
T27S
0
1
MILE
UTAH
GREEN R.
THIS
MAP
COL. R.
MOAB
A
A'
R20E | R21E

Figure 1

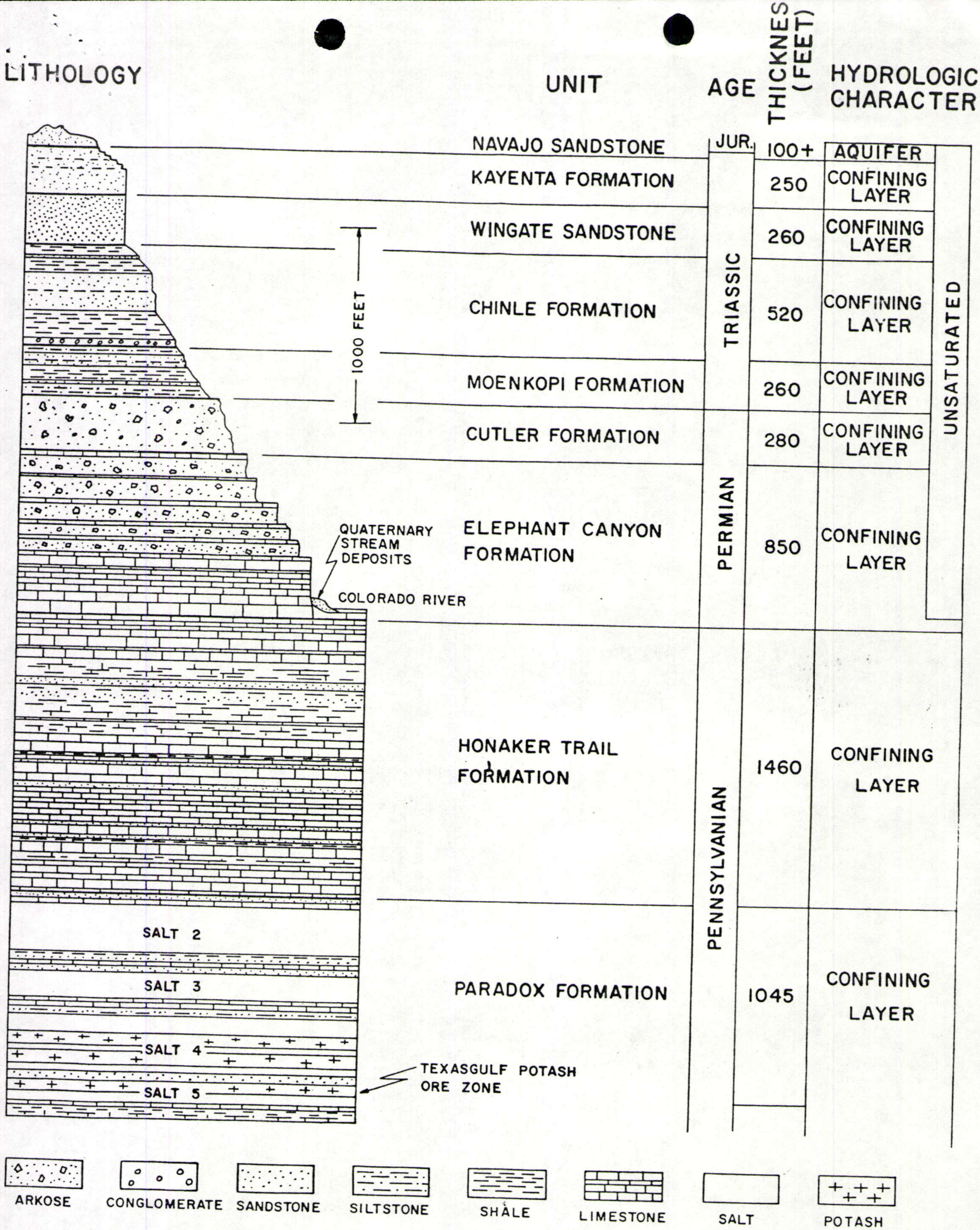
LITHOLOGY
UNIT
AGE
THICKNESS (FEET)
HYDROLOGIC CHARACTER
NAVAJO SANDSTONE
JUR.
100+
AQUIFER
KAYENTA FORMATION
250
CONFINING LAYER
WINGATE SANDSTONE
260
CONFINING LAYER
1000 FEET
CHINLE FORMATION
TRIASSIC
520
CONFINING LAYER
UNSATURATED
MOENKOPI FORMATION
260
CONFINING LAYER
CUTLER FORMATION
280
CONFINING LAYER
QUATERNARY STREAM DEPOSITS
ELEPHANT CANYON FORMATION
PERMIAN
850
CONFINING LAYER
COLORADO RIVER
HONAKER TRAIL FORMATION
1460
CONFINING LAYER
PENNSYLVANIAN
SALT 2
SALT 3
PARADOX FORMATION
1045
CONFINING LAYER
SALT 4
TEXASGULF POTASH ORE ZONE
SALT 5
ARKOSE
CONGLOMERATE
SANDSTONE
SILTSTONE
SHALE
LIMESTONE
SALT
POTASH

Figure 2

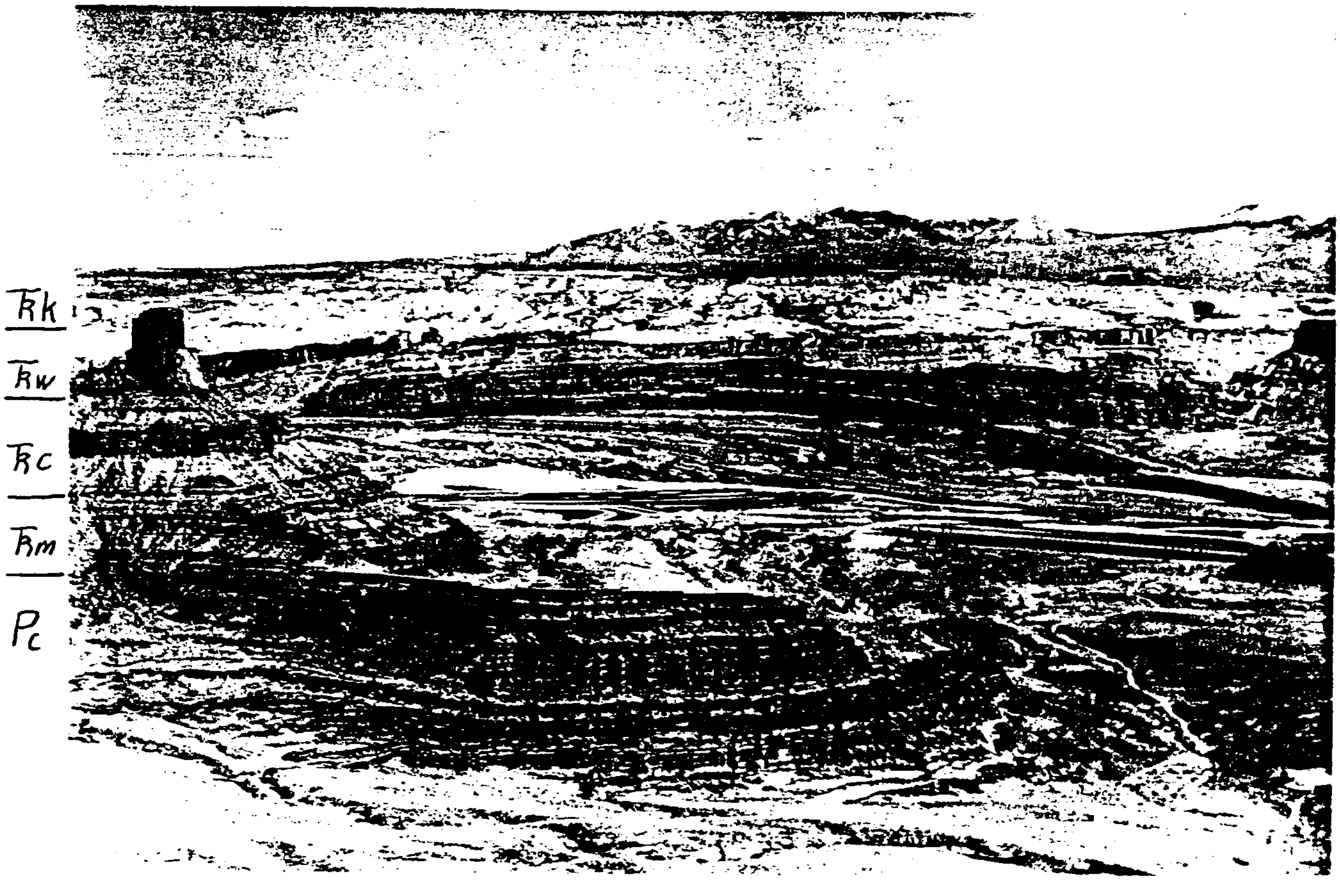

Figure 3

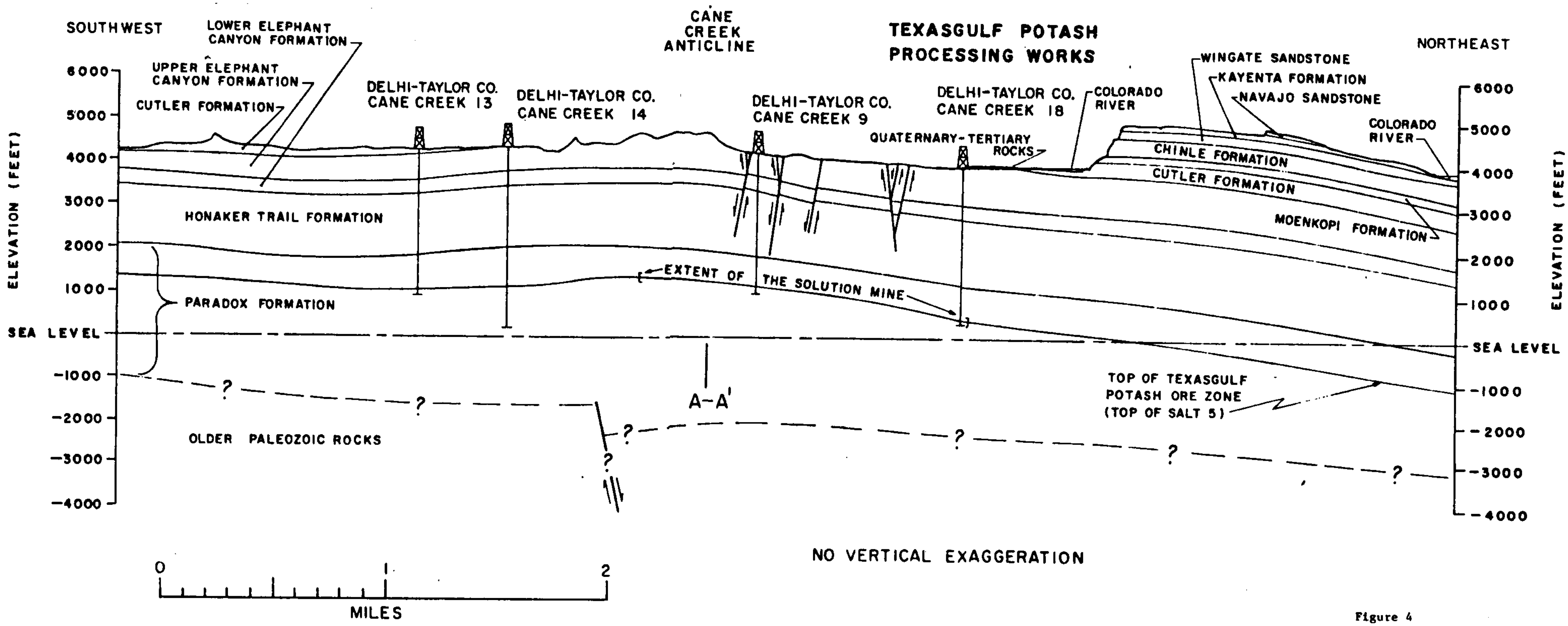
SOUTHWEST
NORTHEAST
CANE CREEK ANTICLINE
TEXASGULF POTASH PROCESSING WORKS
LOWER ELEPHANT CANYON FORMATION
UPPER ELEPHANT CANYON FORMATION
CUTLER FORMATION
DELHI-TAYLOR CO. CANE CREEK 13
DELHI-TAYLOR CO. CANE CREEK 14
DELHI-TAYLOR CO. CANE CREEK 9
DELHI-TAYLOR CO. CANE CREEK 18
QUATERNARY-TERTIARY ROCKS
COLORADO RIVER
WINGATE SANDSTONE
KAYENTA FORMATION
NAVAJO SANDSTONE
COLORADO RIVER
CHINLE FORMATION
CUTLER FORMATION
MOENKOPI FORMATION
HONAKER TRAIL FORMATION
PARADOX FORMATION
EXTENT OF THE SOLUTION MINE
SEA LEVEL
OLDER PALEOZOIC ROCKS
A-A'
TOP OF TEXASGULF POTASH ORE ZONE (TOP OF SALT 5)
ELEVATION (FEET)
6000
5000
4000
3000
2000
1000
-1000
-2000
-3000
-4000
NO VERTICAL EXAGGERATION
0
1
2
MILES

Figure 4

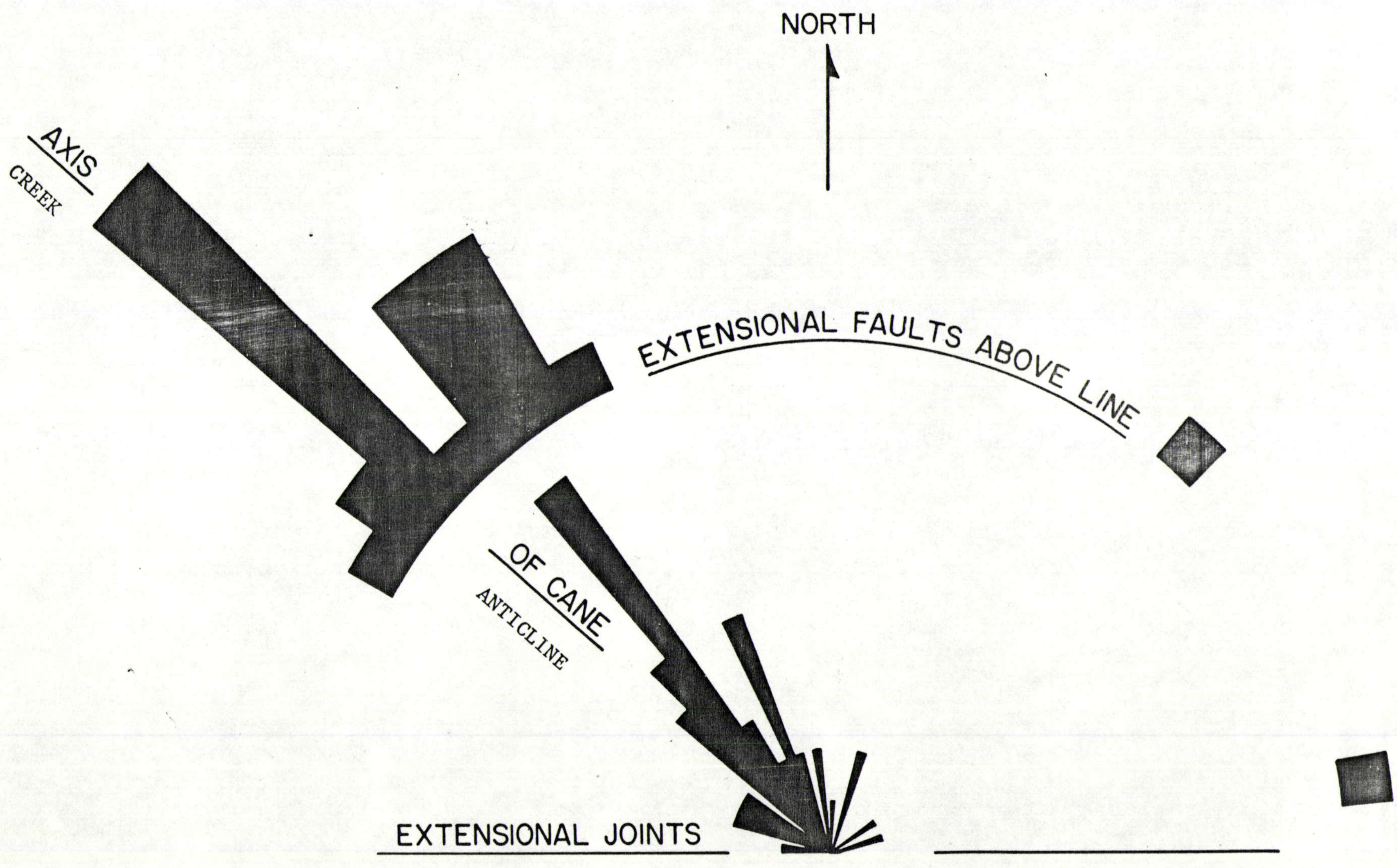
NORTH
AXIS
CREEK
EXTENSIONAL FAULTS ABOVE LINE
OF CANE
ANTICLINE
EXTENSIONAL JOINTS

Figure 5

Figure 6

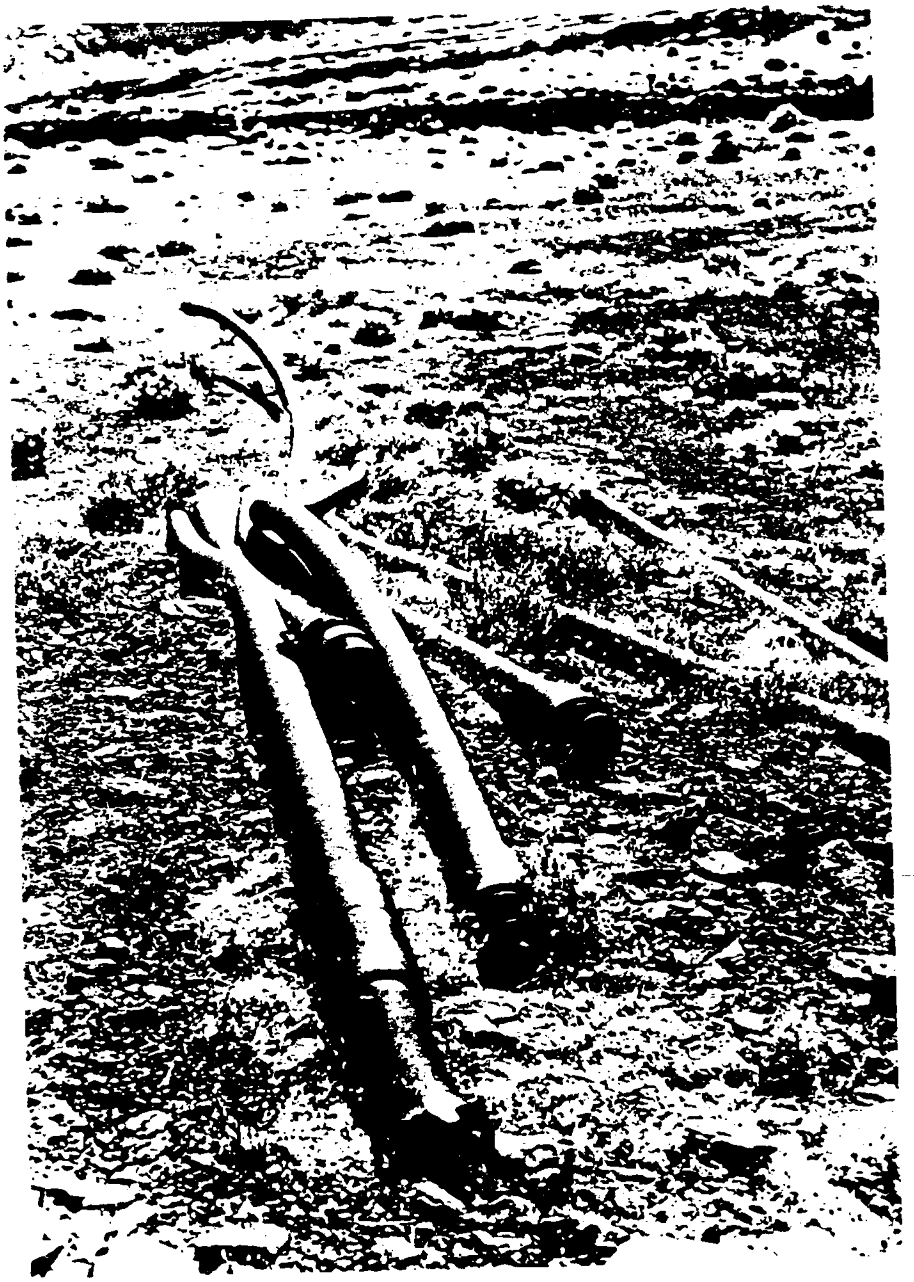

Figure 7